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High resolution measurement of bedload transport

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Abstract:

A bedload movement detector of novel design was installed in a gravel-bed stream as a component of the ongoing research on sediment transport dynamics in the Stuart–Takla Experimental Watersheds in north-central British Columbia, Canada. The device is designed to collect information on the patterns and timing of bedload transport during a flood event. The device is based on a passive magnetic sensor that produces signals of 10^{-2} to 10^{-5} V as its magnetic field is disturbed by passing clasts. A series of 82 sensors is housed in an aluminum beam placed across the stream, inserted such that its surface is flush with the gravel bed. The device can be raised or lowered to compensate for bed aggradation and scour. A data acquisition system gathers voltage signals from the sensors at rates of 30 to 100 Hz. This device is sensitive enough to record the movement of most volcanic, metamorphic, granitic and ultramafic clasts larger than a few millimetres.

O'Ne-ell Creek watershed is a 68 km^2 tributary basin of the Middle River drainage system in the northern headwaters of the Fraser River. Bedload transport generally occurs twice a year in the Stuart–Takla streams: once during spring floods and again during salmon spawning activity. Bedload moved only during two days in 1998, at the peak of the relatively small nival flood in May. Nevertheless, the device detected at least 3×10^6 passing clasts. A continuous record of bedload transport was obtained, showing: a pulsating pattern of activity seemingly independent of stage, lateral movement of the transport zone, and a sudden onset of bed movement with a tapered cessation.

We anticipate that more sophisticated calibration of the sensors and accelerated sampling rates will provide detailed information on the size and/or velocity and magnetic permeability of particles moving over the device, and will contribute to a better understanding of bedload transport. Copyright © 2000 John Wiley & Sons, Ltd.

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INTRODUCTION

Sediment supply and transport processes in steepland areas tend to be very episodic. This is very much the case in many of the steep montane watersheds of British Columbia, where bedload movement occurs for several weeks during spring nival floods and occasionally during brief summer and autumn floods. High discharge events will deliver tons of coarse rock along the bed, creating new bedforms, and armouring the channel. In addition, salmon may move significant amounts of bed material by redd excavation during their annual spawning periods. Bedload movement is a poorly understood phenomenon, and yet is a crucial process in maintaining the hydraulic energy balance of the waterway and providing habitat for many stream dwellers.

Although many theoretical models and equations have been proposed to explain transport of coarse sediments within a gravel-bed river, accurate field observations of the timing and rate of movement, and of

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the presence of active 'zones' within a stream's cross-section are difficult to obtain. The relationship between stream discharge and the entrainment and deposition of bed particles remains vague. Under steady rates of water discharge, unsteady pulses of bedload movement are commonly reported (Ashmore, 1988; Bunte, 1992, 1996; Ergenzinger *et al.*, 1994; Carling *et al.*, 1998). Within a stream cross-section we find zones that exhibit higher rates of transport than others. Clearly, this presents a challenge in terms of sampling adequately across a channel width. The temporal variations in bedload transport rates can occur on several scales (Reid and Frostick, 1994). Sediment pulses can occur over time periods ranging from a few seconds to several months. This non-uniform variation in transport volumes has caused much difficulty in establishing representative sampling methods (Gomez and Troutman, 1997). As a result, there is a noted lack of data on transport rates in gravel-bed rivers.

Studies with tracer stones and scour chains have revealed a great deal about the net changes from sediment transport and deposition within a stream reach. Repeated topographic surveying of the bed is another field method that has provided information about the net volumetric change of bed material and the migration of bedforms within a reach (Ferguson and Ashworth, 1992; Lane *et al.*, 1994; Poirier, 2000). Instantaneous observations, however, require more sophisticated, often permanently installed, equipment. Studies that have managed to collect continuous data during bedload movement events have done so using a number of sampling strategies. Three of the more common types of apparatus are described below.

Net and basket samplers

The standard sampler for bedload is the Helley–Smith sampler with a 3 by 3 inch or a 6 by 6 inch opening and a bag that holds about 10 kg of sediment and has a 0·25 mm mesh width (Emmett, 1980). Other researchers have rigged mesh nets over a solid frame that spans part of the stream, and these are emptied periodically throughout an event (Bunte, 1996). Clearly, net samplers give the best representation of pebbles in motion. They do not, however, gather any of the finer material. They also require a substantial effort, and yet the samples may not be large and/or frequent enough to be statistically representative.

Buckets and pit traps

These consist of a bucket or tube sunk vertically into the bed (Hollingshead, 1971; Church *et al.*, 1991; Powell and Ashworth, 1995), usually with an inner sleeve that can be emptied. Sampling by this method can yield a good estimate of the total mass of sediment moved during the flood event. One successful modification of this technique was the placement of a pillow within the trap well to weigh sediment as it accumulated (Reid *et al.*, 1980). The main disadvantage of traps is that they may soon fill up and, unless closely monitored, have little use in sampling at high rates of sediment discharge.

In situ magnetic detection devices

These devices record the magnetic signals of clasts with implanted magnets or, in the case of more sensitive instruments, the faint signals from remanent magnetism in iron-containing clasts. Ergenzinger and Conrady (1982) installed a device consisting of four large coils 250 mm in diameter attached to an aluminum frame 0·8 m above the water surface at Buonamico, Italy. It registered the passage of 100 cobbles with implanted magnets. The Birkbeck Bedload Sampler, installed at Turkey Brook, Enfield Chase, UK (Reid *et al.*, 1984) used a metal detector circuit with a single 2·3-m-long sensor installed within the streambed. This device was sensitive enough to detect movement of 100 artificial clasts tagged with ferrite rods.

Ergenzinger and Custer (1983) reported a more sensitive instrument consisting of two 1·25-m coils buried horizontally in the streambed at Squaw Creek, Montana. This device could detect naturally magnetic pebbles and cobbles > 32 mm at a rate of two per second. As only a portion of the stream was instrumented, bedload volumes were estimated for the total stream cross-section.

In 1986 a more sophisticated device was installed in Squaw Creek (Custer *et al.*, 1986; Bunte, 1996). The device consists of five sets of paired multiple choke-coil units mounted in a beam set lengthwise across the stream. Each module is 1·55 m long. It thus provides some spatial resolution for different sections of the channel. The placement of two arrays of microcoils 15 cm apart permits the determination of the travel time of passing clasts (Custer *et al.*, 1987; Spieker and Ergenzinger, 1987). The sensitivity of this device permits detection of an estimated 40% of the coarse material (> 32 mm) at Squaw Creek (Bunte, 1996).

All of these devices have used strip chart recorders, which limit their utility to several signals per second and a few sensor circuits. Impulses must be evaluated and counted visually and are usually summed over intervals ranging from 10 min to 1 h. The practical limit of resolution of the strip recorder system in use at Squaw Creek may be 200/h (Bunte, 1996). Consequently, the passage of many clasts may be missed owing to limitations of the data-logging system. Although the device is well suited to recording the relative intensity of bedload activity, it remains an onerous task to quantify volumes.

The present device has taken full advantage of the accurate acquisition and high storage capacities of the current generation of microcomputers. With reasonable spatial resolution (10 cm sensor 'lanes'), activity across the full width of the channel can be recorded at rates of 100 Hz or higher. Using signal processing software, tools such as digital filters and spectral analysis can be applied to quantifying the total mass and the timing of bedload movement.

THE STUDY SITE

Our bedload movement work has been in the Stuart–Takla experimental watershed (Figure 1), where a number of studies have been carried out on fisheries and forestry topics. The bedload movement detector was installed in O'Ne-ell Creek (also known as Kynoch Creek), approximately 150 km north of Fort St James in central British Columbia. It is a third-order tributary of Middle River, which runs southward from Takla Lake, between the Omenica Mountains to the west and the Hogem Range to the east. The O'Ne-ell Creek watershed (Figure 2) encompasses about 68 km^2. The bedload movement detector site is located above the Tsitsutl Creek confluence, where the drainage area is about 38·5 km^2.

The watershed above the detector site is undisturbed by human activities. Large amounts of woody debris, abundant riparian growth, and ample gravels in the bed make this river an important spawning locale for sockeye salmon. Frequent inputs of large woody debris create a forced pool–riffle morphology (Montgomery *et al.*, 1995) throughout much of the stream. The study reach has a gradient of 1·3%, and although there is a large log jam 65 m upstream of the detector site, there is little debris adjacent to the bedload movement detector. The device is on a relatively straight reach of about 100 m. Sediment finer than 1 mm makes up 1% to 10% of the streambed. Bedload ranges from coarse sand to small boulders with diameters up to 30 cm. A dozen samples of the mobile portion (upper 15 cm) of the streambed were taken with a freeze-core sampler, and four large sieve samples were taken on 1 m^2 plots. The D_{50} is about 42 mm and the D_{90} about 128 mm. Nival discharge through the reach ranges up to about 5 m^3/s.

The average annual precipitation in the O'Ne-ell watershed is about 60 cm. Rainfall peaks during June and July and late August–September. Snowfall from November to April accounts for about 50% of the precipitation. Summer season temperatures frequently exceed 20°; winter temperatures are frequently below $-20°$ (MacDonald *et al.*, 1992).

The upper reaches of the watershed are quite steep, with alpine areas up to 2000 m. Outcrops of bedrock along the stream contribute granitic and sedimentary rocks and various ultramafic clasts to the stream bedload. As the stream approaches its alluvial fan, at about 690 m, the gradient becomes increasingly subdued.

PREVIOUS STUART–TAKLA BEDLOAD STUDIES

Several studies (Gottesfeld, 1998; Poirier, 2000) have been undertaken in the past 6 years in order to establish the rates and magnitude of bedload movement in two streams within the Stuart–Takla study area. Forfar and O'Ne-ell Creeks (Figure 1) were chosen as suitable sites to compare the effects of flooding and salmon spawning activity on bedload movement. Both creeks see an average returning population of approximately 12000 salmon each year during the Early Stuart sockeye run.

Studies with over 1000 tracer stones were undertaken from 1992 to 1998 (Gottesfeld, 1998). Some 13000 recoveries of tagged clasts were made after flood events or sockeye redd excavation. The results from this study posited that the amounts of bedload moved by spawning salmon bioturbation are similar to those of floods, although sockeye bioturbation of the streambed did not move the rocks as far as a flood event.

A series of intensive total station surveys of stream reaches clearly showed the annual pattern of stream bedform change (Poirier, 2000). Computer-generated digital elevation models illustrated the morphological effects that each event exerted on the streambed, i.e. linearized features after a flood, and more prominent, hummocky features after the salmon had overturned the gravel substrate.

From these studies some understanding of the magnitude of bedload movement and how it affects channel morphology was gained, but there was still a lack of information on the timing of the gravel movement. To

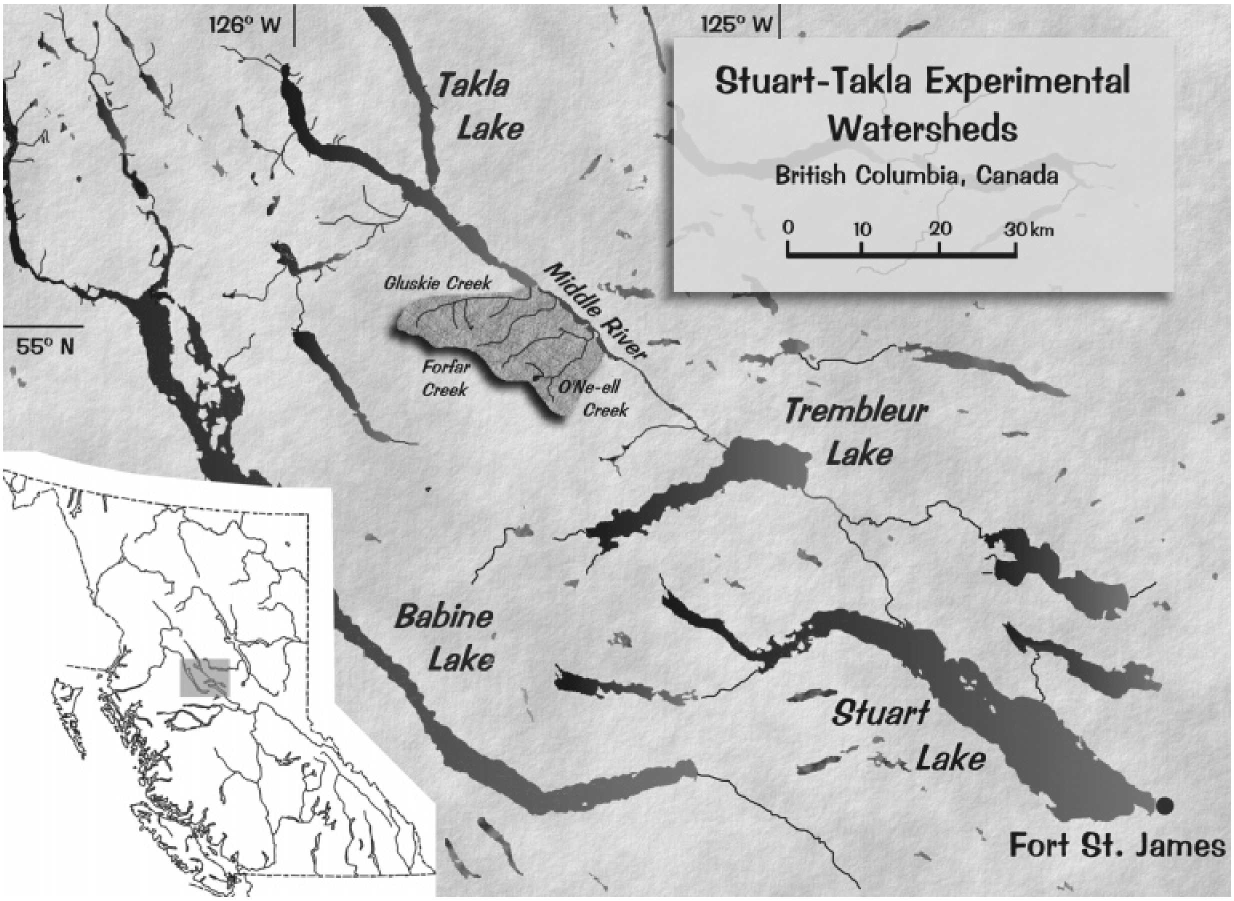

Figure 1. The Stuart–Takla experimental watersheds

this end, we developed a device that may offer some indication of how much gravel is passing a cross-sectional line on the bed with sufficient acuity to see individual particles pass the detectors.

THE UNIVERSITY OF NORTHERN BRITISH COLUMBIA (UNBC) BEDLOAD MOVEMENT DETECTOR

The device consists of a series of magnetic sensors aligned within a square tubular housing unit, buried flush with the streambed. Stream flow and sediment pass over the device with minimal disturbance of near-bed fluid dynamics and sediment transport. The rugged, waterproof detector is constructed of 1/4 inch aluminum stock, and has an adjusting mount on each end, so that it can be raised or lowered to accommodate channel scour or fill (Figure 3).

The device was manufactured to the specification of the study site channel dimensions. The prototype spans a stream width of 8·4 m. A similar design can be used on most streams, to a maximum practical installation size of 30 m in width. The prototype contains 82 sensors, each 8 cm in diameter, spaced at 10 cm intervals. Wires from each sensor run the length of the beam and out to an instrument enclosure adjacent to the stream.

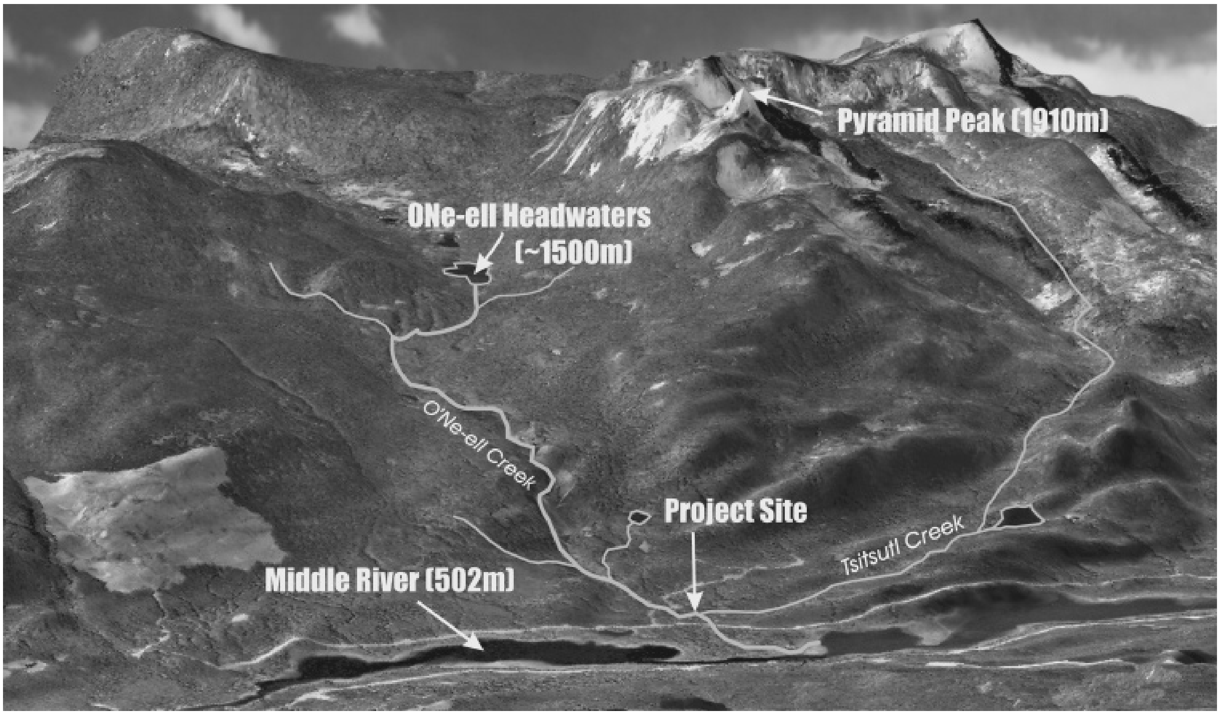

Figure 2. The O'Ne-ell Creek watershed. The bedload movement detector site is located on O'Ne-ell Creek, above the confluence of Tsitsutl Creek

A solar panel array and a backup generator have been installed at the site. A series of telecommunications batteries have sufficient storage capacity to power the computer and data acquisition systems for several days without strong sunshine.

THE SENSORS

The sensors consist of a copper-wound coil mounted within a torus-shaped magnet. The elements are set and water-proofed within epoxy resin, all contained in a steel housing. As a rock, or any ferrous body, passes over the face of the sensor, the magnetic field of the sensor will be distorted. This induces an electromotive force with a potential of 1×10^{-6} to 1×10^{-1} V. A steel casing confines the magnetic field of each sensor, and thus it will respond only to objects passing directly over its face, within a vertical range of approximately 5 cm.

In order to obtain an accurate profile of passing sediment particles, voltage information from each sensor is sampled at rates ranging from 30 to 100 Hz. The largest clasts may be expected to trigger two or more sensors as they pass over the device. Noise in the range of $1{\cdot}5 \times 10^{-4}$ V is inherent in the data acquisition system. Thus, even though the sensor is receptive enough to detect single sand grains, most or all such signals are lost in this field application.

DATA ACQUISITION

An industrial data acquisition system was obtained in order to handle the high volumes of data generated by the sensors. With 82 channels sampling voltages at 100 Hz, a typical field data logger would be quickly overwhelmed. The microvolt range of the sensors also necessitated a system with a high signal-to-noise ratio. Six analogue-to-digital boxes, with 16 channels each, collect the voltage signals from the sensor array. There are signal conditioning amplifiers for each channel. A low-pass Butterworth filter removes signals with a frequency greater than 40 Hz. The filtered data are recorded to disk for more sophisticated signal processing. We are currently using removable hard disks to record the data at rates of up to 120 megabytes per hour. These files are subsequently archived on recordable CDs for storage.

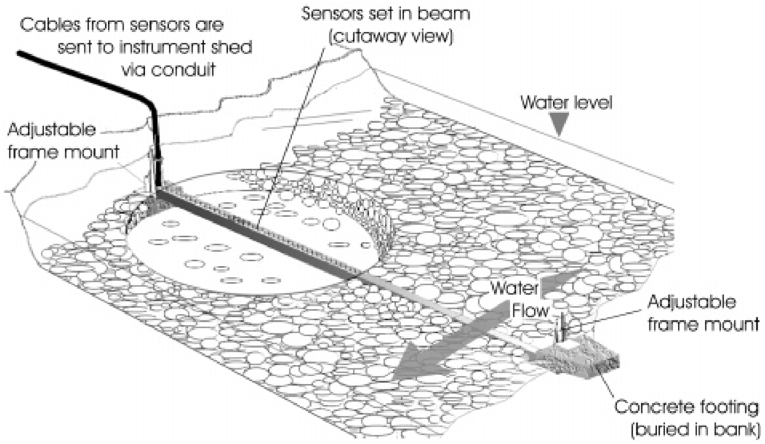

Figure 3. Schematic of the bedload movement detector. The device is buried flush with the streambed surface. Vertical adjustment can be made with threaded rods on the frame mounts

CALIBRATION

The magnetic intensity of the clasts in O'Ne-ell Creek vary over four orders of magnitude (0·1 to 200 milligauss). We have recorded the signals of 200 rocks in the laboratory ranging in mass from 2 to 1200 g. It appears that at least 30% of the bed material > 4 mm contain sufficient magnetic minerals to yield a distinct signal with the bedload movement detector.

The amount of the magnetic minerals, magnetite, chromite and phyrrhotite, in a clast will govern the amplitude of the signal. Clasts that yield strong signals include a variety of lithologies: volcanic rocks, granodioritic to gabbroic plutonic rocks, serpentinized ultramafic rocks, metasediments and metavolcanic clasts.

In streams with a uniform clast lithology we could expect the voltage of the induced signal to be an index of clast size. Because of this unusually great variation in magnetic properties at O'Ne-ell Creek, we have not attempted to determine clast size by the amplitude of induced response, but by other characteristics of the signals.

Figure 4 shows that the same rock, passing over a sensor at decreasing velocities will have a corresponding drop in signal intensity and augmentation in wavelength. The area under the sine wave is similar, but the signal is flattened as the velocity decreases.

Figure 5 shows a graph of 71 rocks passed over the sensors at a constant velocity of 2·25 m/s. By measuring the duration of the sensor's voltage response for each particle, an 'apparent' size of the passing clast is calculated. Despite much experimental error the slope of the fitted curve is very close to 1. Although some stones have complex magnetic properties with varying magnetic strengths across the clast, there is a direct relationship between the size of the clast and the duration of the voltage signal induced by its passage over the sensor.

The wavelength, or frequency, of the signal from a passing clast is a function of both its size and velocity. As we can neither assume that the size of the particles is constant, nor that their velocities are constant, we

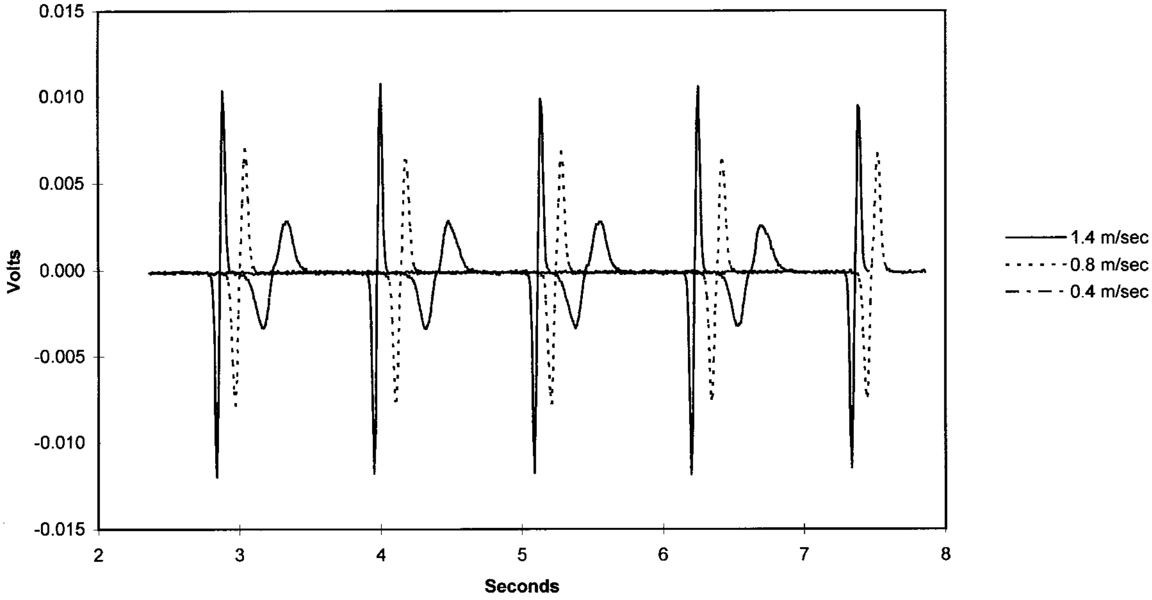

Figure 4. Signals of a greenschist clast mounted on a pendulum passing over a detector at three velocities. Note that the signal intensity increases with increased velocity. The traces are offset in time for clarity

must develop some statistical algorithms to extract pertinent information from the data. Given that we know the size distribution of the bed material and can measure water velocities, the distribution of signal wavelengths in a given period will probably inform us about the range of velocities and/or sizes of clasts in motion. Furthermore, when particles in the cobble range are entrained, we should expect that at least two adjacent sensors will peak at the same instant a cobble traverses the device, leaving another clue as to the size range in motion.

PATTERNS OF BEDLOAD TRANSPORT

Using LabView® signal processing software, the signals from each sensor were normalized, and a low-pass filter cut off high-frequency interference. An example showing data from the peak of nival bedload movement (26 May 1998) is shown in Figure 6. In Figure 6a a single event on sensor number 50 is shown across a 1 s timeline. To the right (Figure 6b) is 15 s of data from this single sensor, with the first signal highlighted within the series. Figure 6c shows an intensity graph of all 82 sensors (i.e. the stream width) over the same 15-s interval. The top of the diagram is the true right bank of the stream. The threshold voltage ($1{\cdot}5 \times 10^{-4}$ V) was exceeded 395 times, indicating the passage of at least that many particles, which probably ranged in size from < 5 mm to 150 mm.

In order to visualize and compare sections of data across many hours or days, 30-s 'chunks' were plotted as a single value of summarized activity across all channels. The peak 24 h of bedload activity is show in Figure 7. Whereas shorter, more sporadic occurrences of activity could be seen before and after this period, by far the bulk of the activity took place in this segment. The discharge reached approximately 6 m^3/s when the hydrograph peaked at 0300 hours. Power outages and disk changes account for the breaks in the record.

As the event began, most of the activity registered in the centre left-hand section of the channel. As the event progressed, approximately 80% of the channel width was mobilized, until the activity shifted to the right-hand side at about 0300 hours. Three large pulses can be discerned in the graph: one starting at midnight, the next at about 0815 hours, and another, smaller one at about 1630 hours. In each case the onset of activity is quite abrupt, and tapers off over the course of 8 h or so. Gaps along the length of the transport

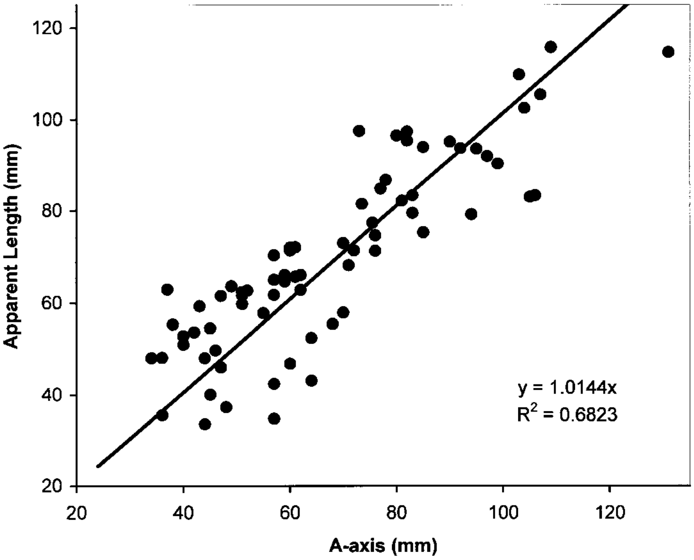

Figure 5. A comparison of clast size versus the 'apparent' clast size calculated from analysis of the voltage signal from a sensor

record probably indicate obstruction of sediment transport, possibly due to boulders coming to rest upstream of the device.

A one-clast-thick carpet of sediment 1·5 m wide covered a section of the left-hand channel, which is seen in the chart as a grey zone. The low intensity probably results from the increased distance of moving clasts from the sensors. Bright high intensity patches represent movement of clasts when patches of the covering layer were removed and/or unusually strong signals.

The pulsing nature of the transport activity can be seen more clearly in Figure 8, which shows an enlargement of the chart at around 1700 hours. Distinct 'waves' of sediment movement can be seen here, with a periodicity of about 20 min. This phenomenon of discrete low-frequency surges can be observed throughout the record. Over the course of the peak 24 h of bedload activity we recorded at least 2×10^6 signals exceeding the threshold voltage.

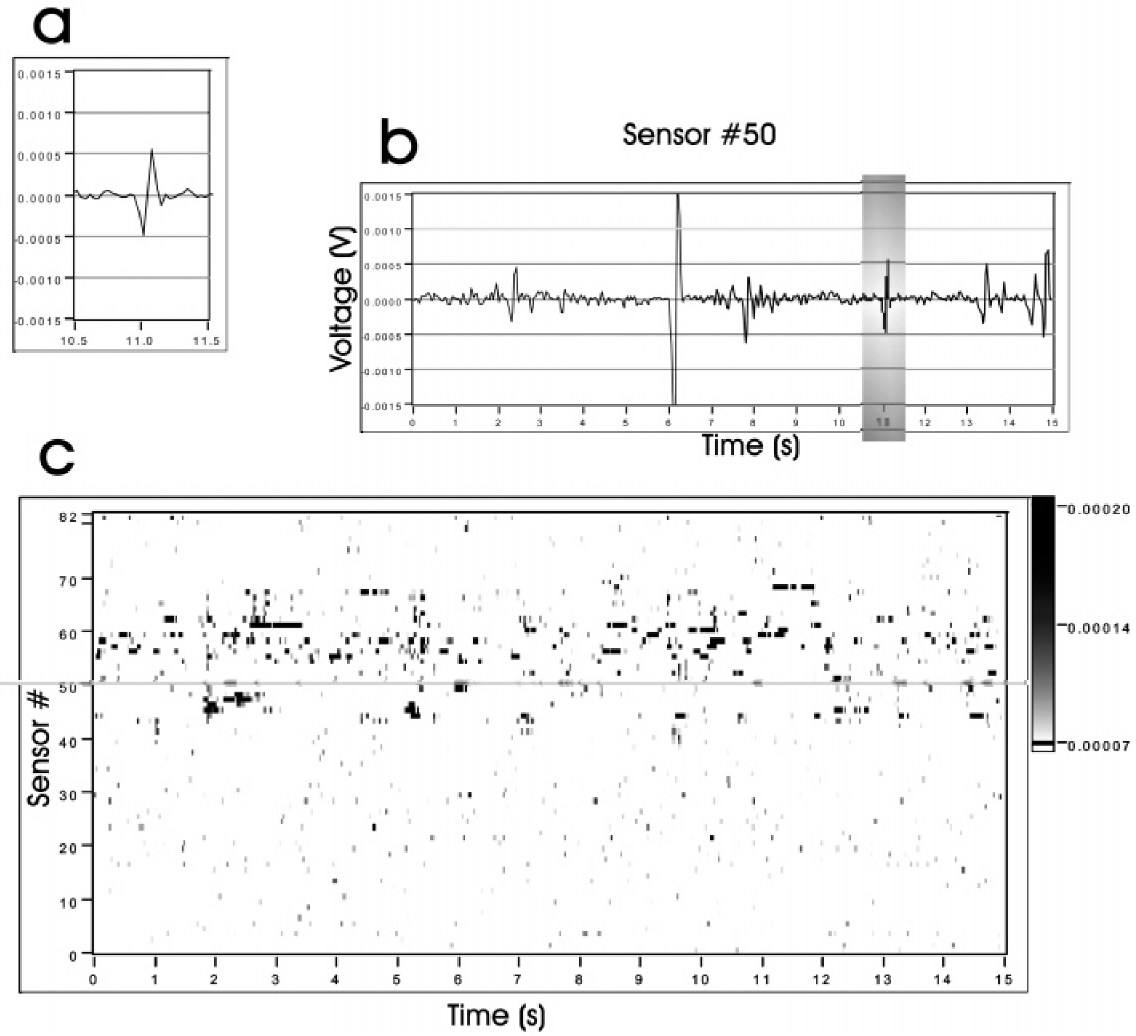

Figure 6. Typical data from the bedload movement detector, collected near the height of bedload transport on 26 May 1998. The vertical scale in (a) and (b) is in volts. In graph (c), signal voltage is shown with a grey scale

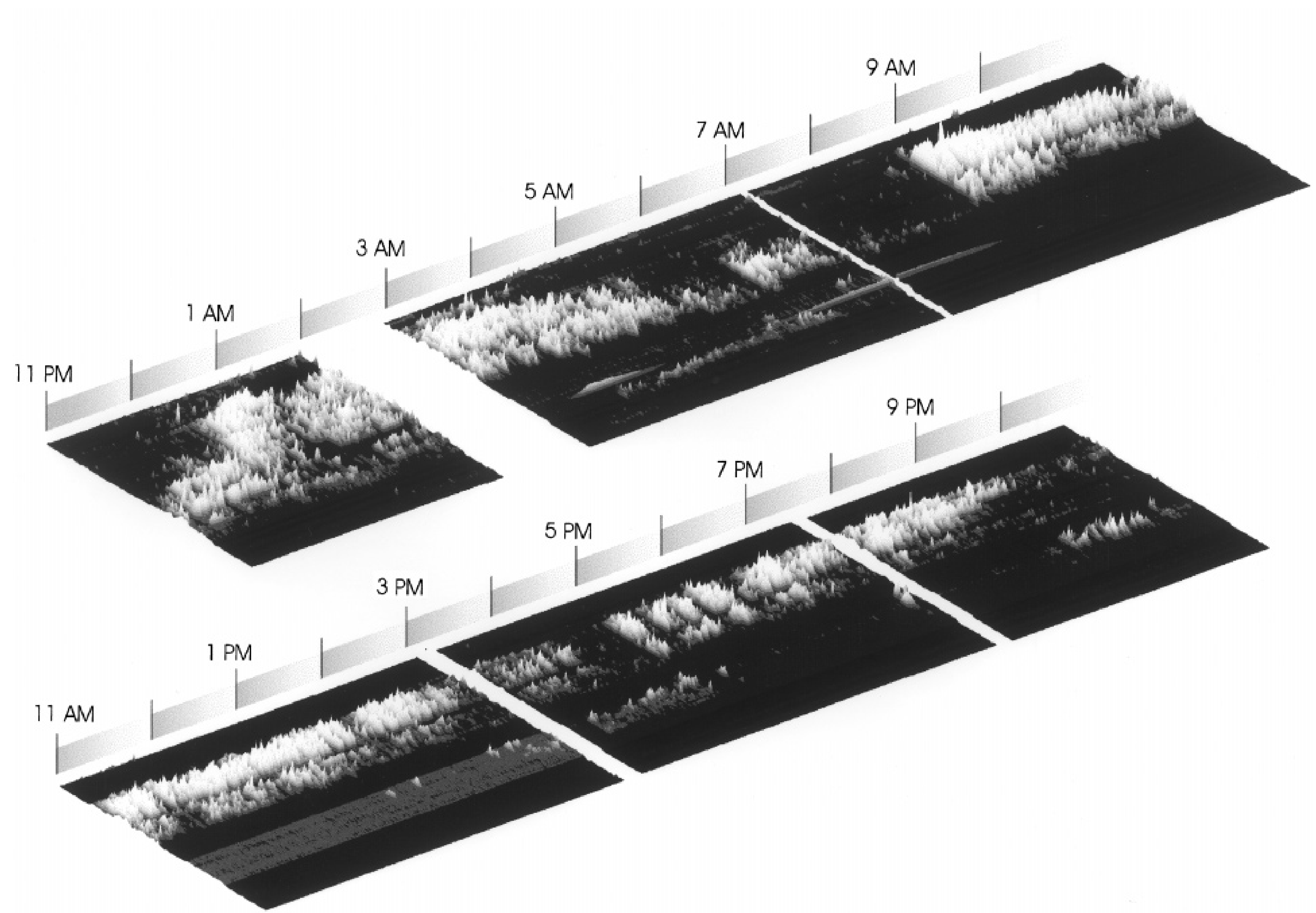

Figure 7. The peak 24 h of bedload movement activity at O'Ne-ell Creek on 25–26 May 1998. Signals from the passage of clasts are summed over 30-s intervals. The diagram represents activity along a cross-section. The right bank of the stream is on the upper edge of the diagram. See text for discussion

FUTURE DIRECTIONS

Snow accumulation in 1997–98 was about 27% below normal and the 1998 nival melt season was long with low peak stages owing to prolonged warm temperatures in April and May. The bedload transport event discussed in this paper resulted from a rain event on the declining limb of the nival flow. For the first trial of the bedload movement detector we were lucky to have an easy year. The nival flood data currently being collected is much more extensive.

We intended to collect data on bedload movement as spawning salmon excavated their redds in late July and early August. Unfortunately, record high temperatures in the Fraser River caused poor returns of adult sockeye in 1998, and there was insufficient spawner density to generate bedload movement at the detector site. We anticipate that the 1999 season will yield higher salmon returns to O'Ne-ell Creek.

The data from the May 1998 event was recorded at a sampling rate of 30 Hz. This rate is too slow to catch critical time- and frequency-domain information on passing clasts. It has also been determined that much finer sediment can be characterized at higher rates of sampling. Thus, for the next event, the data acquisition system will be set to run at 100 Hz or faster.

A variety of phenomena have been observed in the data. We note many groups, or 'fronts' of particles moving together. We have been observing very large numbers of signals of short duration, 10^{-2} s or less. These may be due to saltating sand-sized magnetite grains striking the sensors. The distribution of apparent size varies in an interesting and coherent fashion for much of the flood event.

If this type of bedload movement detector were installed in a stream with clasts of uniform magnetic permeability, then the summed voltage signals could be interpreted as transport mass per unit time. On O'Ne-ell Creek we would benefit from installation of a second row of sensors attached to the downstream

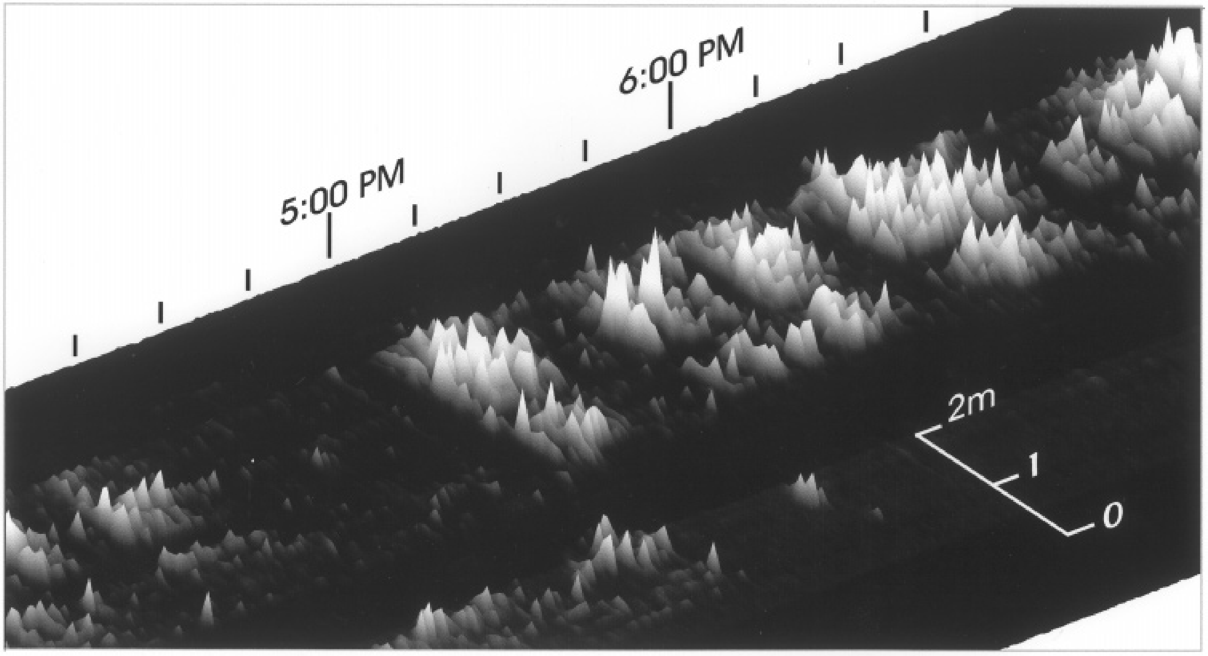

Figure 8. A magnified portion of Figure 7. Within a 3-h period, several distinct 'waves' of sediment movement are apparent

edge of the current device. This would provide more accurate information on the velocity of passing clasts and permit unambiguous determination of clast size.

Finally, as better tools for digital signal processing and spectral analysis are found and applied, it is hoped that on-the-fly processing will cut down on the tens of gigabytes that are currently necessary to capture an event longer than 24 h. Along with more calibration experiments, algorithms for detecting and counting single and complex ('cluster') events are being developed so that a more accurate estimate of sediment volume may be attained. We anticipate being able to automate the data collection once a computer is installed that can reliably initialize itself and begin recording a transport event.

The vast amount of data that this apparatus collects provides a new window for viewing streambed activity and may permit analyses that cast new light on the processes and patterns of bedload transport and provide support for theoretical advances in understanding bedload dynamics.

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